

Little Flavor: Heavy Leptons, Z' and Higgs Phenomenology

Sichun Sun*

Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA and

Institute for Advanced Study, Hong Kong University of

Science and Technology, Clear Water Bay, Hong Kong

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The Little Flavor model [1] is a close cousin of the Little Higgs theory which aims to generate flavor structure around TeV scale. While the original Little Flavor only included the quark sector, here we build the lepton part of the Little Flavor model and explore its phenomenology. The model produces the neutrino mixing matrix and Majorana masses of the Standard Model neutrinos through coupling to heavy lepton partners and Little Higgses. We combine the usual right-handed seesaw mechanism with global symmetry protection to suppress the Standard Model neutrino masses, and identify the TeV partners of leptons as right-handed Majorana neutrinos. The lepton masses and mixing matrix are calculated perturbatively in the theory.

The TeV new gauge bosons have suppressed decay width in dilepton channels. Even assuming the Standard Model couplings, the branching ratios to normal dilepton channels are largely reduced in the model, to evade the bound from current Z' search. It also opens up the new search channels for exotic gauge bosons, especially $Z' \rightarrow \cancel{E}_t + \text{multi } \ell + \text{jets}$. The multiple lepton partners will create new chain decay signals in flavor related processes in colliders, which also give rise to flavor anomalies. The lepton flavor violation process can be highly suppressed in charged lepton sector and happens only through neutrinos.

* sichun@uw.edu

I. INTRODUCTION

The structure and origin of flavor remain mysteries in the Standard Model (SM). There are many models about flavor, although none of them seems particularly convincing. Moreover the majority of the models rely on high scale/short distance to explain the absence of observed electric dipole moments, the small values for the neutrino masses, and flavor changing rare decays such as $\mu \rightarrow 3e$. This is also part of the reason that most flavor models lack experimental proofs.

The Little/composite Higgs theory [2–7] is an alternative to supersymmetry to address the hierarchy problem at low energy. The classes of little Higgs/composite Higgs types of theories now have generated numerous realistic extensions[8–32] and phenomenological studies in colliders[33–42]. It predicts fewer new particles comparing to supersymmetry. Each fermion can have an exotic fermionic partner, Higgses have pseudo Goldstone bosons as partners; The Little/composite Higgs theory uses softly broken nonlinearly realized symmetries to protect the Higgs mass.

The ultra-violet completion of the strong dynamics in little/composite Higgs theory can be directly related to the recent "second string revolution" in 00s. The Ads/CFT correspondence and Randall-Sundrum type of theories indicate that higher dimensional supersymmetric theories are dual to conformal/non-conformal theories in four dimensions through holography,e.g.[12, 43–46]. Supersymmetric theory in very high energy/higher dimensions might be seen in an interesting and unusual way at the low energy, such as low energy theory being "Emergent" [47–49], different from the conventional compactification and supersymmetry breaking.

In reference [1, 49] we took a modest low energy approach, that proposed to extend the Little Higgs theory to use the additional symmetries as flavor symmetries and related the quark masses to the structure of the soft symmetry breaking terms. We found that the resulting model had new flavor physics at the TeV scale but escaped low energy constraints on Flavor Changing Neutral Currents (FCNC).

Fig. 1 shows a way to look at the Little Flavor model in terms of fermions, their partners and couplings. This figure resembles a moose/quiver graph with gauge groups living on each sites. The difference is that the sites are connected by non-linear σ model fields which are in the bi-fundamental representations of the gauge groups. The fermions are in fundamental representations and live on the sites.

Each generation of standard model fermions mostly live on a white site, with a seesaw type mixing with their own partners. The "partners" here mostly live on the adjacent black sites which are coupled to their own standard model companions on white sites through non-linear σ model

fields —the oriented lines in the graph. Each cell contains one black fermion and one white fermion. Due to the fermion multiplet structure, the small mixing across the cells is also directly proportional to the $SU(4)$ symmetry breaking on black sites, which is proportional to the SM fermion mass.

The partner structure in Little Flavor is more complicated, because the breaking of the global symmetry associated with the fermion multiplets are not only responsible for generating the Higgs potential, but also give masses to the Standard Model fermions. In the first Little Flavor model, the chiral fields on white sites have exactly the same field content as the Standard Model, with every one of those chiral fields having a Dirac partner on the black site.

Since SM type mixing, e.g., CKM, PMNS matrix, coming from left-handed W current, are basically describing the misalignment between up-type and down-type fermions in the currents, it can still have considerable amount of flavor off-diagonal matrix elements, while the neutral current are largely suppressed by the small mass of fermions comparing to the cut-off scale.

Fig 2 shows the Little Flavor model in an effective theory, which is further studied in [50]. The Standard Model fermions are coupled to Higgs fields and heavy partners with slightly broken global symmetries.

In this paper, we extend the Little Flavor theory to include leptons, especially we explore a new type of neutrino seesaw by putting neutrinos in a $SU(4)$ multiplet with charged leptons, identifying some fermion partners in the Little Flavor theory as right-handed Majorana neutrinos. The Little Flavor mechanism makes sure that the seesaw mass required by the neutrino mass bounds is no more than a couple of TeVs. We also discuss some phenomenological aspect of Little Flavor, including new search channels in Z' physics, flavor violations and Higgs decay. Especially, the Z' in the model could introduce a recent LHC anomaly in the angular distribution of B meson decay according to [51–54]

II. GAUGE GROUPS

Here we work out the gauge sector in more details, to study the phenomenology. The couplings involving the Higgs sector are discussed in [50]. We further discuss an improved gauge $SU(2) \times SU(2)$ on black site at the end of gauge group discussion.

The gauge symmetry of the model is $G_w \times G_b$, where $G_{w,b}$ are independent $SU(2) \times U(1)$ groups living on white (w) and black (b) sites respectively. The $G_w \times G_b$ break down to the diagonal subgroup of the SM $SU(2) \times U(1)$, and we take the the gauge couplings to be

$$g_{1,w} = \frac{g'}{\cos \gamma_1} , \quad g_{1,b} = \frac{g'}{\sin \gamma_1} , \quad g_{2,w} = \frac{g}{\cos \gamma_2} , \quad g_{2,b} = \frac{g}{\sin \gamma_2} . \quad (1)$$

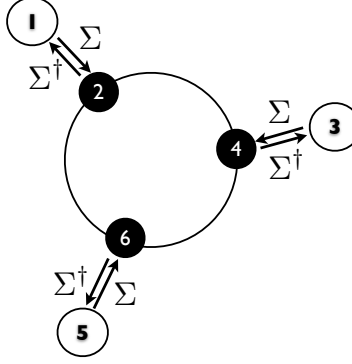


FIG. 1. A deformed moose diagram shows chiral fields on the white sites and their partners on the black sites. The big circle in the middle represents $SU(4) \times U(3)$ breaking terms

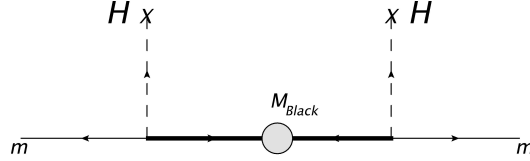


FIG. 2. Simplified effective couplings between the Standard Model fermions and their partners.

with $g = e/\sin\theta_w$ and $g' = e/\cos\theta_w$ are the usual SM gauge couplings and the angles $\gamma_{1,2}$ are free parameters. These couplings are designed to produce the right SM electroweak physics.

The gauge fields are coupled to an $SU(4) \times SU(4)/SU(4)$ nonlinear σ -model, parametrized by the field Σ , an $SU(4)$ matrix which transforms under $SU(4) \times SU(4)$ as the $(4, \bar{4})$ representation, where Little Higgses live. The $G_w \times G_b$ gauge symmetry is embedded in the $SU(4) \times SU(4)$ so that the covariant derivative acts on Σ as

$$D_\mu \Sigma = \partial_\mu \Sigma + i \left(g_{2,w} A_\mu^a T_a + g_{1,w} B_\mu Y \right) \Sigma - i \Sigma \left(g_{2,b} \tilde{A}_\mu^a T_a + g_{1,b} \tilde{B}_\mu Y \right), \quad (2)$$

where $\{A_\mu^a, B_\mu\}$ and $\{\tilde{A}_\mu^a, \tilde{B}_\mu\}$ are the gauge bosons of G_w and G_b respectively.

The Σ field spontaneously breaks $G_w \times G_b$ gauge symmetry down to a diagonal subgroup; if $\langle \Sigma \rangle = 1$, the unbroken subgroup is the diagonal $SU(2) \times U(1)$, which is identified with the electroweak gauge group of the SM, and it has the correct couplings g and g' . The small off-diagonal matrix elements of $\langle \Sigma \rangle = 1$ further breaks EW $SU(2) \times U(1)$ to electromagnetic $U(1)$. There are two exotic Z bosons and an exotic W boson gotten masses from this spontaneously symmetry breaking, whose masses are:

$$M_{Z'} = \frac{gf}{\sin 2\gamma_2}, \quad M_{Z''} = M_{W'} = \frac{g'f}{\sin 2\gamma_1}. \quad (3)$$

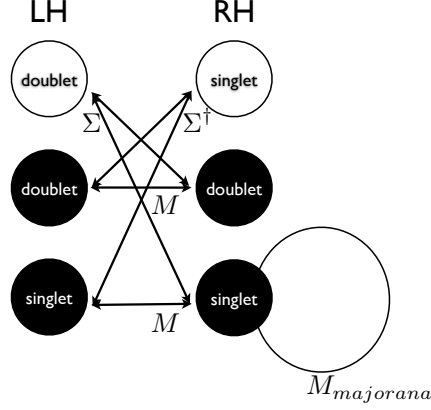


FIG. 3. A graph displays how upper or down type fermion fields respectively in one single cell are coupled to each others. All couplings are from the left-handed fermions to the right-handed fermions, except the right-handed neutrino Majorana mass term for black fermions, that gives neutrino mass extra suppression except for the black partner fermion "seesaw-like" mechanism.

Electroweak symmetry breaking will correct these relations at $O(M_Z^2/f^2)$; in the model we consider in this paper we fix the Goldstone boson decay constant to be $f = 1.5$ TeV; thus the corrections are $O(M_Z^2/f^2) \simeq 1\%$.

This is the same gauge sector we used in the previous quark model paper. The problem with this model is that the gauge couplings explicitly break black fermion $SU(4)$ at one-loop level. Because the key thing of Little Flavor mechanism is this black fermion $SU(4)$ protects fermion mass to prevent FCNC from generating, this is bad for the model and will radiatively generate fermion mass at hundreds of MeV.

One way to fix it is to gauge $SU(2) \times SU(2)$ at black site rather than $SU(2) \times U(1)$, and make upper $SU(2)$ coupling the same as lower $SU(2)$. Then there are two extra W'' :

$$M_{W''} = M_{Z'} = \frac{g' f}{\sin 2\gamma_2} \quad (4)$$

And let $g_{1,b} = g'/\sin \gamma_1 = g_{2,b} = g/\sin \gamma_2$, which leads to:

$$\tan \theta_w = \frac{\sin \gamma_1}{\sin \gamma_2} \quad (5)$$

This would not change phenomenological aspects much.

One could also work out the gauge boson self-coupling, here we stick to $SU(2) \times U(1)$ model:

$$L \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}Z^{\mu\nu}Z_{\mu\nu} - \frac{1}{4}Z'^{\mu\nu}Z'_{\mu\nu} - \frac{1}{4}Z''^{\mu\nu}Z''_{\mu\nu} \quad (6)$$

$$+ \sum_{b,w} \{-D_i^{\dagger\mu}W_i^{-\nu}D_\mu W_i^{+\nu} + D_i^{\dagger\mu}W_i^{-\nu}D_{i\nu}W_i^{+\mu} + ig_{2i}F_{3i}^{\mu\nu}W_{i\mu}^+W_{i\nu}^-\} \quad (7)$$

	WW	WW'	$W'W'$
Z''	0	$-ie$	$ie(\sin^3 \gamma / \cos \gamma - \cos^3 \gamma / \sin \gamma)$
Z'	0	0	0
Z	$ie \cot \theta_w$	0	$ie \cot \theta_w$
A	ie	0	ie

TABLE I. gauge bosons self-coupling in the limit $\gamma_1 \rightarrow \gamma_2 \rightarrow \gamma$. Notice here the physical gauge couplings also include the momentum factor $g_{\mu\nu}(k_2 - k_1)_\rho + g_{\nu\rho}(k_3 - k_2)_\mu + g_{\rho\mu}(k_1 - k_3)_\nu$.

In the limit of $\gamma_1 \rightarrow \gamma_2 \rightarrow \gamma$ (one should note that if it is not in this limit, the mixings between $Z'Z''W'W''$ have non-trivial dependence on γ_1 and γ_2):

$$W_w^\pm = -\sin \gamma W'^\pm + \cos \gamma W^\pm \quad (8)$$

$$W_b^\pm = \cos \gamma W'^\pm + \sin \gamma W^\pm \quad (9)$$

$$F_3^{\mu\nu} = \partial^\mu A_{3i}^\nu - \partial^\nu A_{3i}^\mu \quad (10)$$

$$D_i = \partial_i - ig_i A_{3i} \quad (11)$$

$$A_{3w} = \sin \gamma Z'' + \cos \gamma \cos \theta_w Z + \cos \gamma \sin \theta_w A \quad (12)$$

$$A_{3b} = -\cos \gamma Z'' + \sin \gamma \cos \theta_w Z + \sin \gamma \sin \theta_w A \quad (13)$$

The Σ field describes fifteen pseudo Goldstone bosons with decay constant f , to be set to 1.5 TeV in the phenomenological model we studied in the previous work [1]. With different parameter values γ_1, γ_2 , the triple-gauge couplings present here can explain the recent diboson anomalies in WW, ZZ, WZ channels [55–58]. We are not exactly sure how the recent 750 GeV resonance [59, 60] fits into the model yet, possibly one of the Higgs partners in Σ can be a good candidate. The parametrization of Σ here is given by [1].

III. FERMION CONTENT AND MASS TERMS

The model could be described by the deformed moose diagram of Fig. 1, which is not a normally defined moose. The oriented links represent Σ and Σ^\dagger , while the white and black sites represent fermions transforming nontrivially under G_w and G_b respectively. The big circle in the middle shows the mixing across the paired sites.

One could construct leptons as $SU(2)$ doublets $L = (n, e)$ and $SU(2)$ singlets N, E . The black fermions are Dirac fermions, which are made of left-handed and right-handed components, packed

together as the quartets of approximate $U(4)_b$ symmetries

$$\psi_b = \begin{pmatrix} L \\ N \\ E \end{pmatrix}_b, \quad \text{black sites: } b = 2, 4, 6. \quad (14)$$

The white fermions are chiral fermions, which have the exactly same field content as the Standard Model fermions:

$$\chi_{w,L} = \begin{pmatrix} L \\ 0 \\ 0 \end{pmatrix}_{w,L}, \quad \chi_{w,R} = \begin{pmatrix} 0 \\ N \\ E \end{pmatrix}_{w,R}, \quad \text{white sites: } w = 1, 3, 5. \quad (15)$$

$b = 2, 4, 6$ and $w = 1, 3, 5$ refer to the site numbers in Fig. 1.

The G_w and G_b gauge generators are embedded within $U(4)_{w,b}$ as in Σ field, except that Y is extended to include a term $\frac{1}{2}(B - L) = \frac{1}{6}$ for all the fermions to produce the right hypercharge, this is universal for both quarks and leptons:

$$Y = \begin{pmatrix} 0 & 0 \\ 0 & T_3 \end{pmatrix} + \frac{1}{2}(B - L) = \begin{pmatrix} 0 & 0 \\ 0 & T_3 \end{pmatrix} - \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (\text{Leptons}) \quad (16)$$

where the leptonic fermions all carry $(B - L) = -1$. The $SU(2)$ part in $G_w \times G_b$ only gauges the upper part of the multiplets, the doublets.

To compact the mass term, we label the cells by $n = 1, 2, 3$, with cell n associated with sites $\{2n - 1, 2n\}$, and then an index $\alpha = 1, 2$ will specify the white and the black site respectively within the cell. The fermions are all labeled then as $\Psi_{n,\alpha}$ with

$$\Psi_{1,1} = \chi_1, \quad \Psi_{1,2} = \psi_2, \quad \Psi_{2,1} = \chi_3, \quad \Psi_{2,2} = \psi_4, \quad \Psi_{3,1} = \chi_5, \quad \Psi_{3,2} = \psi_6, \quad (17)$$

where the χ four-component chiral fermions on the white sites in eq. (15), and the ψ are the four component Dirac fermions on the black sites in eq. (14).

To get the electroweak symmetry breaking and neutrino Majorana masses we introduce two spurions to break the $SU(4) \times U(3)$ symmetry, defined by the traceless 4×4 matrices which can be thought of as transforming as elements of the adjoint of $SU(4)$:

$$X_m = X_N = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 1 & \\ & & & 0 \end{pmatrix}, \quad X_E = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix} \quad (18)$$

These matrices break the $SU(4)$ symmetry down to $SU(3)$ and will allow the light fermions to acquire masses; the X_E matrix splits off the E charged leptons from the $SU(4)$ multiplet, while X_N distinguishes the N neutrinos. We write all the mass term as below:

$$\mathcal{L} = \mathcal{L}_{\text{sym}} + \mathcal{L}_{\text{asym}} + \mathcal{L}_{\text{asym,majorana}} \quad (19)$$

The symmetric fermion mass and Yukawa terms are given by

$$\mathcal{L}_{\text{sym}} = \bar{\Psi}_{m\alpha,L} \left[\mathcal{M}_{m\alpha,n\beta} + \Sigma \mathcal{Y}_{m\alpha,n\beta} - \Sigma^\dagger \mathcal{Y}_{m\alpha,n\beta}^\dagger \right] \Psi_{n\beta,R} , \quad (20)$$

where \mathcal{M}, \mathcal{Y} are independent and take the form

$$\mathcal{M}_{m\alpha,n\beta} = M_{\text{black}} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}_{mn} \otimes \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}_{\alpha\beta} \quad (21)$$

$$\mathcal{Y} = \lambda_{Yukawa} f \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}_{mn} \otimes \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}_{\alpha\beta} , \quad (22)$$

where all unmarked matrix elements are zero.

The \mathcal{M} term is a common mass term for the black site Dirac fermions; the \mathcal{Y} term is a nearest neighbor hopping interaction involving Σ, Σ^\dagger in the direction of the link arrow. Note that these hopping terms combined look like a covariant derivative in a fifth dimension, with Σ playing the role of the fifth component of a gauge field. This could also be interpreted as the terms in lattice gauge theory with finite lattice sites.

X_m projects out neutrino field. We take for our symmetry breaking mass terms

$$\mathcal{L}_{\text{asym}} = \bar{\Psi}_{m\alpha,L} [\mathcal{M}_{m\alpha,n\beta}^E + \mathcal{M}_{m\alpha,n\beta}^N] \Psi_{n\beta,R} \quad (23)$$

where

$$\mathcal{M}_{m\alpha,n\beta}^E = M_{mn}^E \otimes \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}_{\alpha\beta} \otimes X_E , \quad \mathcal{M}_{m\alpha,n\beta}^N = M_{mn}^N \otimes \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}_{\alpha\beta} \otimes X_N . \quad (24)$$

Those terms are the couplings between black fermions. It is represented in the big circle in Fig. 1.

The $\mathcal{M}_{m\alpha,n\beta}^E, \mathcal{M}_{m\alpha,n\beta}^N$ are 3×3 matrices which contain textures.

Extra symmetry breaking majorana mass term:

$$\mathcal{L}_{\text{asym,majorana}} = \Psi_{m\alpha,R}^T (\mathcal{M}_{m\alpha,n\beta}^m) \Psi_{n\beta,R} \quad (25)$$

$$\mathcal{M}_{m\alpha,n\beta}^m = M_{mn}^m \otimes \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}_{\alpha\beta} \otimes X_m . \quad (26)$$

$$M_{mn}^m = M_{\text{majorana}} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}_{mn} \quad (27)$$

Where X_m projects out neutrino field N of whole multiplet, and $\mathcal{M}_{m\alpha,n\beta}^M$ is a real Majorana mass matrix.

By having the X spurions each leave intact an $SU(3)$ subgroup of the black-site $SU(4)$ symmetry, we ensure that the fermions will not contribute any one-loop quadratically divergent mass contributions to the Higgs boson (the Little Higgs mechanism). Although it is not important in the lepton sector at current TeV scale due to the smallness of lepton masses. The extra ingredient here comparing to the quark sector is the Majorana masses. We will show how to construct the mass matrix from this Lagrangian later in the Appendix.

IV. A TEXTURE AND EFFECTIVE MASS FORMULAS

We can choose a simplest texture which agrees with experimental results on lepton masses and mixing matrix. This choice is not unique. The interesting thing about this particular texture is to explicitly put all the flavor violation effect in neutrino sector to evade the stringent bounds in charged lepton sector:

$$M^E = D_E, \quad M^N = U_{NH}^T \cdot D_N . \quad (28)$$

With

$$D_E = \begin{pmatrix} M_e & & \\ & M_\mu & \\ & & M_\tau \end{pmatrix}, \quad D_N = \begin{pmatrix} M_{\nu_e} & & \\ & M_{\nu_\mu} & \\ & & M_{\nu_\tau} \end{pmatrix}, \quad (29)$$

And U_{NH} being the unitary lepton mixing matrix for normal hierarchy. One can also chose the texture for the inverse hierarchy.

In this model, one can easily integrating out heavy particles, and all the Standard Model lepton masses are perturbative. Following the analysis of EFT , we arrive at mass formulas for neutrinos and leptons:

$$m_n = \frac{(D_N)^2}{M_{majorana}} \frac{v_n^2}{f^2} \frac{(\lambda_Y f)^2}{(\lambda_Y f)^2 + M_{black}^2} [1 + O(\frac{M_{black}^2}{M_{majorana}^2})] \quad (30)$$

$$m_e = \frac{v_n}{f} \frac{(\lambda_Y f)^2}{(\lambda_Y f)^2 + M_{black}^2} D_E [1 + O(\frac{D_E}{M_{black}})] \quad (31)$$

Note see-saw mechanism from right-handed M^m for neutrinos, and the extra factor $(\lambda f)^2/[(\lambda f)^2 + M^2]$ from wave function renormalization, equivalent to the effect of mixing with heavy vector-like leptons. It is also straightforward to see that this texture correctly produces the neutrino mixing matrix U_{NH} .

V. A REALISTIC SOLUTION

In order to show the spectrum of all the new particles and compute heavy gauge boson couplings to the fermions, we choose to parametrize the model as below

$$f = 1500 \text{ GeV}, \quad \lambda_{Y,Lepton} = 0.1498 \quad (32)$$

$$M_{black} = 500 \text{ GeV}, \quad \tan\beta = \frac{v_n}{v_e} = 1 \quad (33)$$

$$M_{majorana} = 5000 \text{ GeV} \quad (34)$$

Note that the size of composite coupling f is shared with quark sector, while leptons have their own universal Yukawa coupling, which is one-tenth of quark Yukawa. The mass scale of heavy lepton partners is 500 GeV, which makes the lightest lepton partners be about 200 GeV. Considering the experimental bound of charged leptons, about 100 GeV [61], It is also possible in the model to have even lighter lepton partners.

To have the lighter fermion partners, one could tune down M_{black} , then it is necessary to also have smaller $\lambda_{Y,Lepton}$ due to the fact that the ratio $M_{black}/\lambda f$ is directly related to the mixing of right-handed and left-handed particles. If the SM left-handed particles have too much right-handed component which is coupled to W boson, we will end up with non-unitary mixing matrix.

Choose the input in heavy lepton mass matrix as the PDG valued U_{NH}

$$U_{NH} = \begin{pmatrix} 0.822 & 0.547 & -0.15 \\ -0.355 & 0.702 & 0.616 \\ 0.442 & -0.452 & 0.772 \end{pmatrix} \quad (35)$$

Then one will have SM lepton mixing matrix as:

$$U'_{NH} = \begin{pmatrix} 0.818 & 0.551 & -0.147 \\ -0.363 & 0.701 & 0.61 \\ 0.44 & -0.446 & 0.776 \end{pmatrix} \quad (36)$$

U'_{NH} is the mixing matrix computed from the full theory. In Appendix.A we show the detail of computation: generating the mixing matrix and mass spectrum from full theory. Notice that

$$U'_{NH}U_{NH}^\dagger = \begin{pmatrix} 0.9950 & 0 & 0 \\ 0 & 0.9950 & 0 \\ 0 & 0 & 0.9957 \end{pmatrix} \quad (37)$$

The non-unitarity of PMNS matrix at 0.5% is due to both the mixing with heavy lepton partners and right-handed particles. The non-unitarity bound for the PMNS matrix is discussed in [62, 63]. Although 0.5% seems to be in tension with the newest bounds, we conclude it is still not clear about the unitarity bound in the LF model, because [62, 63] assumed only the SM particle spectrum.

We also choose the eigenvalues of the mass texture to be as below, these are the parameters that feed into the SM particle masses.

$$D_N = \begin{pmatrix} 2.278 \times 10^1 & 0 & 0 \\ 0 & 2.319 \times 10^1 & 0 \\ 0 & 0 & 2.541 \times 10^1 \end{pmatrix} \text{ MeV}, \quad (38)$$

$$D_E = \begin{pmatrix} 2.611 \times 10^1 & 0 & 0 \\ 0 & 5.444 \times 10^3 & 0 \\ 0 & 0 & 1.069 \times 10^5 \end{pmatrix} \text{ MeV} \quad (39)$$

The full mass spectrum, including all the partners are, For Dirac-like charged leptons (in GeV):

$$(647.2, 553.1, 548.2, 548.2, 548.2, 548.2, 1.773, 1.056 \times 10^{-1}, 5.110 \times 10^{-4}) \quad (40)$$

For neutrinos, note that there is the mass splitting for right-handed and left-handed particles:

$$\begin{aligned} & (5050, 5050, 5050, 548.2, 548.2, 548.2, \\ & 548.2, 548.2, 548.2, 248.3, 248.3, 248.3, \\ & 198.6, 198.6, 198.6, 2.974 \times 10^{-10}, 2.482 \times 10^{-10}, 2.393 \times 10^{-10}) \text{ GeV} \end{aligned} \quad (41)$$

VI. Z', Z'' AND W'

Here we choose $\gamma_1 = \gamma_2 = \pi/8$, to be comparable to the quark sector, which gives rise to $M_{Z'} = 750$ GeV, $M_{Z''} = 1400$ GeV. One could easily go to different values of γ_1, γ_2 to accommodate $SU(2) \times SU(2)$ model. The gauge bosons are coupled to the Standard Model fermions as below, as the vector basis being $\{e, \mu, \tau\}$ and $\{\nu_e, \nu_\mu, \nu_\tau\}$. The neutral gauge boson couplings are strictly flavor diagonal, due to the choice of M^N in this paper, which only has the texture matrix on the left.

Another interesting thing is the reduced Z', Z'' coupling comparing to the SM Z, which is due to the choice of free parameters γ_1, γ_2 , one can see the further analysis in [50]. One could fine-tune them to completely decouple Z', Z'' , but it is not necessary. We can see later that even SM model-like couplings are enough to evade the current bounds because of the extensive lepton sector.

$$L_Z^n = \begin{pmatrix} 3.627 & 0 & 0 \\ 0 & 3.627 & 0 \\ 0 & 0 & 3.627 \end{pmatrix} \times 10^{-1} \quad (42)$$

$$L_{Z''}^n = \begin{pmatrix} -1.919 & 0 & 0 \\ 0 & -1.919 & 0 \\ 0 & 0 & -1.919 \end{pmatrix} \times 10^{-2}, L_{Z'}^n = \begin{pmatrix} 1.229 & 0 & 0 \\ 0 & 1.229 & 0 \\ 0 & 0 & 1.229 \end{pmatrix} \times 10^{-2} \quad (43)$$

$$R_Z^e = \begin{pmatrix} 1.613 & 0 & 0 \\ 0 & 1.613 & 0 \\ 0 & 0 & 1.617 \end{pmatrix} \times 10^{-1}, L_Z^e = \begin{pmatrix} -2.006 & 0 & 0 \\ 0 & -2.006 & 0 \\ 0 & 0 & -2.008 \end{pmatrix} \times 10^{-1} \quad (44)$$

$$R_{Z''}^e = \begin{pmatrix} 1.204 & 0 & 0 \\ 0 & 1.197 & 0 \\ 0 & 0 & 1.078 \end{pmatrix} \times 10^{-3}, L_{Z''}^e = \begin{pmatrix} 1.86 & 0 & 0 \\ 0 & 1.859 & 0 \\ 0 & 0 & 1.851 \end{pmatrix} \times 10^{-2}, \quad (45)$$

$$R_{Z'}^e = \begin{pmatrix} 2.12 & 0 & 0 \\ 0 & 1.834 & 0 \\ 0 & 0 & -2.43 \end{pmatrix} \times 10^{-2}, L_{Z'}^e = \begin{pmatrix} 9.896 & 0 & 0 \\ 0 & 9.859 & 0 \\ 0 & 0 & 9.296 \end{pmatrix} \times 10^{-3} \quad (46)$$

We can define the charged current according to the normalization below:

$$- \frac{g_2}{\sqrt{2}} \left(W_\mu^+ \bar{N}_i \mathcal{L}_{ij}^W \gamma^\mu P_L E_j + W_\mu'^+ \bar{N}_i \mathcal{L}_{ij}^{W'} \gamma^\mu P_L E_j \right). \quad (47)$$

$$L_W = \begin{pmatrix} 7.902 \times 10^{-1} & 5.324 \times 10^{-1} & -1.422 \times 10^{-1} \\ -3.504 \times 10^{-1} & 6.773 \times 10^{-1} & 5.889 \times 10^{-1} \\ 4.253 \times 10^{-1} & -4.312 \times 10^{-1} & 7.494 \times 10^{-1} \end{pmatrix}, \quad (48)$$

$$L_{W'} = \begin{pmatrix} 4.652 \times 10^{-2} & 3.134 \times 10^{-2} & -8.35 \times 10^{-3} \\ -2.063 \times 10^{-2} & 3.987 \times 10^{-2} & 3.457 \times 10^{-2} \\ 2.504 \times 10^{-2} & -2.538 \times 10^{-2} & 4.4 \times 10^{-2} \end{pmatrix} \approx L_W \frac{M_W}{M_{W'}} \quad (49)$$

Notice that $L_W \approx V_{pmns}$. There are couples of interesting physics process related to these couplings:

1. As in previously discussed quark sector, Z' couplings to quarks are smaller than Z couplings by a factor of around 10^{-2} , and the Z'' and W' couplings to quarks are suppressed by about an order of magnitude relative to the Z and W couplings. These suppressions reduce the production rates of new gauge boson dramatically. They are also enough to satisfy current collider bounds for jet, top quark and gauge boson final states [64–69].
2. We can see here Z', Z'', W' couplings to leptons are suppressed by at least an order of magnitude relative to the Z and W couplings. More importantly, the branching ratios to the Standard model leptons are quite reduced, because all the lepton partners except RH Majorana neutrinos in current parameter choices are lighter than these new gauge bosons, which could have more decay channels rather than those in the Standard model. Thus those Z', Z'' are still allowed for the current dilepton final states of Z' search [70–74], including the newest 13TeV run II [74]. Moreover, the reduced coupling of Z' to leptons will also satisfy the electroweak precision constraints. See the discussion of constraints on Z' in [75].
3. We can also see that the new physics mediated FCNC are at loop level through W' exchange, or with heavy leptons mediated penguin diagrams. Note that there is similar GIM suppression with $L_{W'}$, new physics FCNC contribution will occur at the same loop level but much smaller than the standard model ones.
4. It is not likely to see tree level flavor-changing charged current contribution to neutrino oscillation experiments in the current model set-up due to $L_{W'} \propto L_W$. With more texture built into M^E, M^N , we will be able to see the deviation from long base line neutrino oscillation experiments due to W' mediated oscillations.

	ll		Ll		LL		NN	Nn	nn
	L	R	L	R	L	R			
Z	0.20	0.161	$=< 0.02$	$=< 0.02$	0.2	0.2	0.36	$=< 0.01$	0.36
Z''	0.019	0.0011	$=< 0.34$	$=< 0.04$	0.63	0.77	0.70	$=< 0.02$	0.019
Z'	0.0098	0.02	$=< 0.18$	$=< 0.4$	0.83	0.72	0.378	$=< 0.13$	0.012

TABLE II. Z', Z'' couplings at tree level

	ln	Ln	lN	LN
W	V_{pmns}	$\sim V_{pmns} M_w / M_{w'}$	$=< 0.02$	$=< 0.6$
W'	$V_{pmns} M_w / M_{w'}$	$\sim V_{pmns}$	$\sim V_{pmns}$	$=< 1$

TABLE III. W' exotic decay channels

5. There are non-zero coupling between the Z', Z'', W' and heavy lepton partners, both diagonal and off-diagonal ones. One could calculate it to estimate the size of different branching ratio for other channels of new gauge bosons. We will talk about it more in the next section.
6. We expect sizable contributions to the muon magnetic moment rising from the Z' gauge boson, in particular. Although the M'_Z is at the TeV scale, those corrections are actually proportional to $M_L^2 / M_{Z'}^2$, which can be big enough to explain the muon magnetic moment anomaly. This discussion is further explored in [76].

VII. NEW PHYSICS PROCESS

A couple of hundreds GeV lepton partners can mediate some new processes. Here below L or N stands for heavy exotic charged lepton partners and heavy neutrinos while l, n are the SM leptons. For Z' search, the new processes could be summarized as below:

1. $Z' \rightarrow Ll \rightarrow nnll$ or $Z'' \rightarrow W'^+ W'^- \rightarrow nnll$
2. $Z' \rightarrow NN \rightarrow nnllll$

	ll	Ll		LL
h_{sm}	λ_{yukawa}	$\sin \frac{v}{f}$	$\cos \frac{v}{f}$	$=< 0.01$

TABLE IV. Higgs couplings. Note that $\lambda_{yukawa} \sim 0.01$ for τ in the Standard Model. All the couplings are flavor-diagonal. The heavy to light couplings are only between SM fermions and their own partners.

It is also possible to have longer decay chain of Z' , to have more than 4 leptons final states.

$$3. Z'' \rightarrow W^+W'^- \rightarrow W^+lN \rightarrow W^+W^+ll \rightarrow 4jets + ll$$

For W' search, there are also multi-lepton final states: $W' \rightarrow Nl \rightarrow nlll$ or $W' \rightarrow nL \rightarrow nnnl$.

From the tree level couplings listed in the table, one could see that over 95% Z', Z'', W' decays go to multi-leptons and E_{tmiss} final states rather than the Standard Model type di-muons or e^+e^- , which are under 1%. Detailed branching ratios depend on specific parameters in the model, such as γ_1, γ_2 in the gauge sector. Multi-leptons plus missing energy final states have been heavily studied in supersymmetry search [77–79], and some recent study in the context of vector-like quark extension [80, 81]. $Z'Z''W'$ masses being 700 and 1400 GeV are above the current bounds, but it may provide future guide for Z' search. Especially reconstructing two same sign W from $4jets + ll$ final states could be a distinct signature for this type of models.

Although it is not in this particular choice of parameters, but it is also possible to have lepton partners even lighter than the Higgs boson, but heavier than current bounds from LEP [61]. The $L(*)$ or $N(*)$ stands for a heavy lepton or a virtual heavy lepton.

$$1. h \rightarrow L(*)l, N(*)n \rightarrow nnll \rightarrow \cancel{E}_T + ll$$

This type of exotic decay final states of Higgs exists in some supersymmetry models as discussed in [82, 83]. However, due to the large Llh couplings as in the table below, this scenario is most likely to be ruled out for heavy leptons mass smaller than 125 GeV from current Higgs branching ratio data. The lepton partners behave much like top/quark-partners in terms of the Higgs couplings. The vector-like quarks are constraint by LHC [84, 85], and there are extensive literatures about top-partner search e.g.[86, 87]. The lepton partners are less discussed, and will be more probed in future generation colliders like ILC, CEPC and FCC-ee.

VIII. CONCLUSION

The Little Flavor model [1, 49] provides a new direction for the TeV flavor physics, while in the same time extends the Little Higgs models. It also alleviates the fine-tuning problem in the Little Higgs theory. Fermions get masses in this new mechanism through the breaking of vector-like symmetries associated with exotic vector-like Dirac fermions and an approximate nonlinear

symmetry in the Higgs sector. It suppresses FCNC only by a $U(2)^2$ vector symmetry rather than $U(2)^5$ chiral symmetry in Minimal Flavor Violation in the low energy [50], it also provides multiple collider signatures within LHC reach.

In this paper, we focus on the lepton part of the flavor model, and constructed a TeV neutrino see-saw mechanism. The new physics beyond the SM could be observed through Z' and Higgs physics, as experimental proofs.

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Appendix A: Generating 18×18 Mass matrix with Majorana masses

Fig. 3 shows that the couplings between fermions we wrote down. Except the Majorana mass, all the couplings are between left-handed and right-handed particles. For neutrinos, there are totally 9 left-handed field, 3 on each paired site, and 9 right-handed ones. One can construct the 18-vector, with 9 left-handed fields first and then 9 right-handed fields:

$$F = \{L_{n,w}^L, L_{n,b}^L, N_b^L, \dots, N_w^R, L_{n,b}^R, N_b^R, \dots\} \quad (\text{A1})$$

Then the mass matrix can be written in a compact form:

$$\mathcal{L} = F^T M_{18 \times 18} F + h.c. \quad (\text{A2})$$

Diagonalizing the mass matrix yields the neutrino spectrum in eq. 41. According to the parameter choice we used in this paper, the numbers for the mass matrices are as below (in unit GeV):

$$M_1 = \begin{pmatrix} 0. & 223.149 & 26.3591 & 0. & 0. & 0. & 0. & 0. & 0. \\ 26.3591 & 500. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ -223.149 & 0. & 500.019 & 0. & 0. & -0.00823179 & 0. & 0. & 0.0112327 \\ 0. & 0. & 0. & 0. & 223.149 & 26.3591 & 0. & 0. & 0. \\ 0. & 0. & 0. & 26.3591 & 500. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0.0124598 & -223.149 & 0. & 500.016 & 0. & 0. & -0.0114868 \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 223.149 & 26.3591 \\ 0. & 0. & 0. & 0. & 0. & 0. & 26.3591 & 500. & 0. \\ 0. & 0. & -0.00341675 & 0. & 0. & 0.0142839 & -223.149 & 0. & 500.02 \end{pmatrix} \quad (\text{A3})$$

$$M_2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 5000. & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5000. & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5000. & 0 \end{pmatrix} \quad (\text{A4})$$

$$M_{18 \times 18} = \begin{pmatrix} 0 & M_1 \\ M_1^\dagger & M_2 \end{pmatrix} \quad (\text{A5})$$

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